A full scale atmospheric flight experimental research environment for Titan exploration devices

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We propose to develop a full-accuracy flight test environment for Titan, the largest moon of Saturn. The experiment would use reduced-g atmospheric flights with a standard aircraft, with appropriate equipment, including a cooled, possibly pressurized environmental chamber.

INTRODUCTION

Reduced atmospheric density flight has been the object of much interest throughout the history of aviation. Indeed, aviation *is* about reduced air density flight: A jet liner takes off from Boston Logan Airport at sea level. There air density is 1.225 kg/m^3. As it crosses the Atlantic ocean, it reaches an altitude up to 38,000 feet above sea level, where air density is approximately reduced to 1/5th of what it is an the ground. It takes flying up to 100,000 feet above sea level for the atmospheric density to reduce to 1/100th of its sea level density. On Earth, several aircraft are capable of flying at 100,000ft. They include the X15 and the Helios solar-powered aircraft.

In contrast, *increased* atmospheric density flight is much less common, though not negligible. For example, Titan, Saturn's largest moon features a thicker atmosphere than the Earth's, combined with low gravity. Titan is the motivation for this report. Titan's characteristics include a surface gravity of 1.352 m/s^2 and a ground-level atmospheric density of 1.45 atmosphere. NASA and the Jet Propulsion Laboratory (JPL) are in the process of developing conceptual vehicles to be deployed on Titan, Saturn's largest moon. Some of these vehicles are described in recent general news outlets [1]. The "Shapeshifter", a spherical assembly of independent quadrotors, meets the requirements of being capable of both rolling on Titan's surface and of deploying itself as a distributed airborne system too, as shown in Fig. 1.

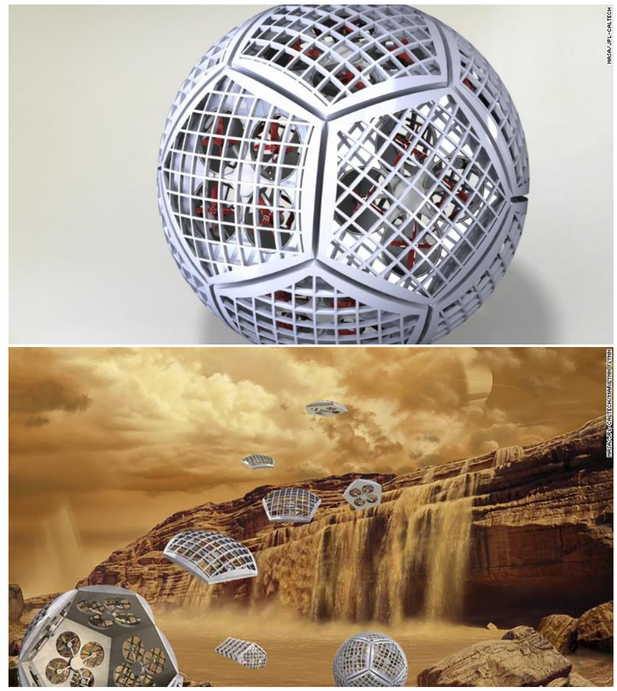

Figure 1. Shapeshifter assembled as a ball and airborne deployment [1]

Currently standing at the conceptual level, engineering studies of the Shapeshifter may be found in Sabet, Agha-Mohammadi et al. [2]. It is worth noting the Shapeshifter is the latest in a series of possible vehicles that include earlier concepts, such as the lighter-than-atmosphere vehicle described in Fathpour, Blackmore et al. [3]

Owing to the costly nature of a mission to Titan, any Earth-based test of the vehicle designed to operate on Titan could tremendously benefit from the most extensive possible Earth-bound tests. The ideal flight test environment would recreate the same gravity and atmospheric conditions as on Titan. The below discussion argues in favor of using reduced-gravity atmospheric flights precisely designed for that purpose. While using the "vomit comet" is well-known in support of studying and anticipating human behavior in weightlessness, and has also been used to study new vehicles operating on low-gravity environments, such as asteroids, using such systems for flight-testing extra-terrestrial flying artifacts is somewhat less known. One opportunity lies with Mars exploration [4], where atmospheric machines are being considered for surveillance and mapping missions. The nature of Titan is different as it features a lower gravity environment and a higher atmospheric density.

REDUCED GRAVITY ATMOSPHERIC FLIGHT

General considerations

Reduced-gravity atmospheric flight consists of using an atmospheric vehicle (typically an aircraft, but not necessarily [5], [6]) that flies along trajectories where a given level of gravity is "felt" in the reference frame of the vehicle. The most popular form of reduced-gravity flight is the zero-g flight, whereby the aircraft follows exactly the part of an Earth orbit to reproduce weightlessness conditions. In practice actual trajectories, inexactly called parabolic trajectories, last on the order of 18 seconds. A variant on zero-g flight is *micro-g* or μg flights, whereby micro-gravity conditions are created to reproduce those encountered in

Figure 2. Various contemporary uses of atmospheric zero-g flights. Top: Experimental research. Bottom: OK Go, 'OK Go - Upside Down and Inside Out' video

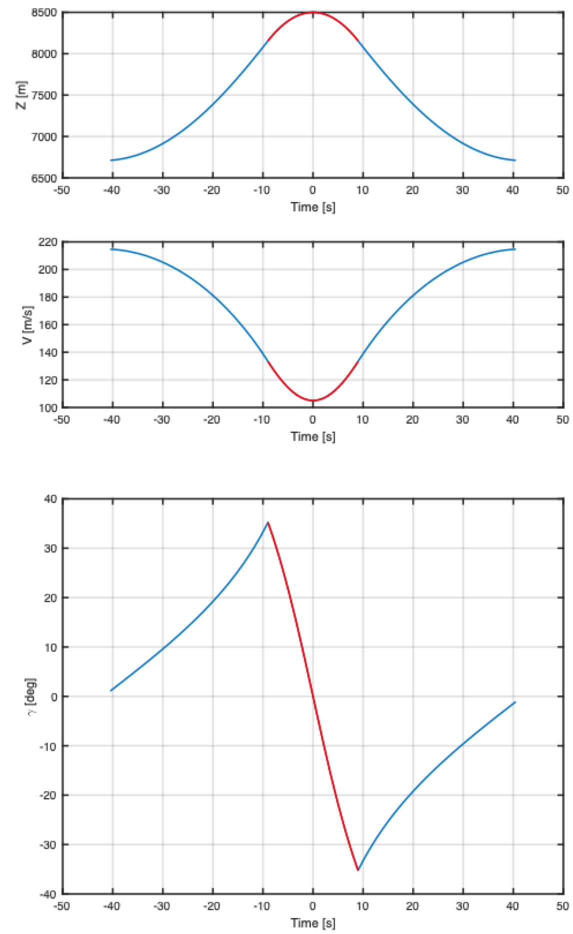

Figure 3. Titan-g trajectories for standard cargo transport aircraft. The Red dashed lines indicate the boundaries of the Titan-g maneuver. Left: aircraft altitude and speed as a function of time (units are second, meters, and meters per second, respectively). Right: Flight path angle.

low-gravity environments, such as asteroids. Accurate μg flights are considerably more difficult to create than zero-g flights: the latter can be easily regulated by a skilled pilot by "controlling" the test aircraft against the reference trajectory provided by a proof mass and deviations from the nominal trajectories do not matter as long as the proof mass does not deviate exaggeratedly from its free-floating position. Coarsely speaking, that means that human and material subjects in floating conditions will also not move much relative to the aircraft fuselage. These zero-g tests not only are very popular to achieve purposes of scientific and engineering interest, but also have been used to make video clips for music bands and define innovative environment for fashion shows, see Fig. 2. In comparison, micro-g is about producing very precise gravity conditions for objects that are *fixed* relative to the aircraft. The proof-mass concept then does not work anymore and very precise regulation needs taking place using other sensors than proof masses.

Creating a Titan gravity environment is similar in nature to the foregoing activities. The point is to create an environment where local gravity is approximately Titan's, that is, 0.138 g (or 1.342 m/s^2). Flying 0.138 g trajectories is nearly the same as flying a zero-g trajectory, only that the near parabolic trajectory of the aircraft must mimic being pulled to the ground in the vacuum with a constant gravitation of 0.862 g instead of 1 g. Such demand on the aircraft is slightly less aggressive than performing a 0-g maneuver, especially during maneuver recovery.

FLIGHT CHARACTERISTICS

The characteristics of an atmospheric flight that recreate Titan-like flight conditions must combine low gravity with high atmospheric density.

Titan-g parabolic flights are similar to those of a standard zero-g flight: after a horizontal, rectilinear acceleration phase, the test aircraft initiates a pull-up maneuver so as to reach the proper initial attitude and speed to perform the Titan-g phase of the flight, which resembles an inverted parabola. Once the Titan-g maneuver is complete, the aircraft pulls up to resume straight and level flight. Other maneuvers may follow along the same principle. The challenges that come with the design of these maneuvers include the necessity to avoid stall at all times on the one hand, and to keep Mach number below transsonic regime, on the other hand. In addition, we have added the constraint that the maneuver be performed by a standard cargo jet aircraft or, alternatively, a specifically modified aircraft, such as the Zero-g corporation's Boeing 727 or the European Space agency's Airbus A310. A maximum aircraft load limit has been placed at 1.3 g for the recovery maneuver.

Figure 4. Typical, flyable environmental chamber.

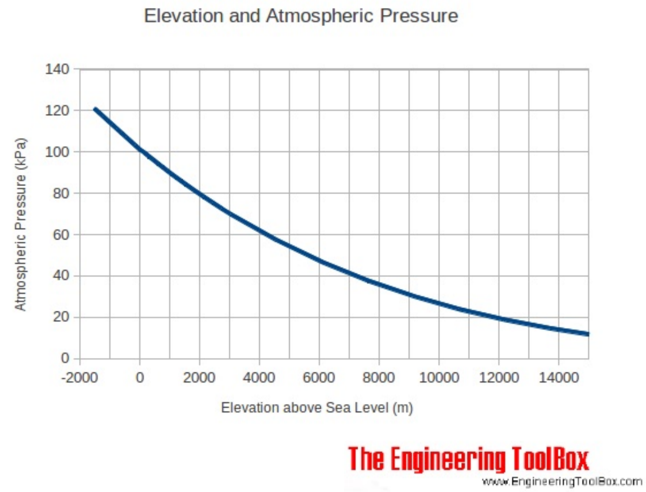

Figure 5. Standard atmospheric pressure vs. altitude on Earth.

Figure 6. Left: Zero-G corporation's 727.

The simulation shown in Fig. 3 indicates that a 20 sec. Titan-g maneuver is achievable without inducing excessive stress on the aircraft during recovery (1.3 g max). The duration of the maneuver constitutes only a lower bound to what is possible. However, it already constitutes a valuable duration for a "flight test withing the flight test". Moreover, the flight path angle does not exceed 35 degrees in magnitude. On top of the maneuver, true airspeed is 105 m/sec, resulting in a maximum angle of attack less than 3 degrees at apogee, well within its stall envelope and indicative of longer possible flight periods over which Titan gravity may be replicated.

ENVIRONMENTAL CHAMBER

While this paper does not intend to enter into the details of the environmental chamber design, several remarks can be made about some of the constraints that must be met before the system can be constructed. During a flight test aimed at replicating Titan atmospheric conditions, there is a combination of very low temperatures and high atmospheric density. Creating such conditions might best be achieved by using environmental chambers developed by companies such as Russels technical products [7] and shown in Fig. 4.

The atmospheric constraints in the aircraft require an internal aircraft altitude pressure to be set in the vicinity of 5,000 ft, or about 1500 meters, which is about 0.8 atm, see Fig. 5

Under these conditions, obtaining an air density equal to 1.45 that of the Earth atmosphere could be obtained by moderately pressuring the foregoing environmental chambers to recover slightly more than 1 atmosphere and operating it at its lowest attainable temperatures (195 K). Several pressure-temperature trade-offs might be considered according to conditions secondary to the experiment under consideration.

Geometric constraints

First, there are the geometric constraints posed by the dimensions of the test aircraft. In short, the bigger the aircraft, the better. As a benchmark, the cargo bay of today's reduced g research aircraft in the US, a 727-200 operated by the Zero-g corporation, is about three-meter wide. Systems such as the Shapeshifter have sufficiently small dimensions (a foot or less) that they can fit well-within the volume offered by any customized or standard commercial aircraft. If the vehicle size increases, then the aircraft size may need to increase.

An important consideration is the necessity to fit an environmental chamber inside the reduced-g aircraft. For that purpose, availability of a large cargo door considerably helps. For example, the 727 of the zero-G corporation offers a large cargo door. Alternatives include the European zero-g flight test aircraft, a converted Airbus A310, see Fig. 7. According to the web site describing the characteristics of the payload bay, see [8], the dimensions of the testing volume are 20 x 5 x 2.3 metres (L x W x H), thus offering superior

Figure 7. ESA A310 zero-g aircraft. Doors are those of a standard commercial jet.

space available for experiments. However, according to the same web site, the door for equipment loading has a height limit of 1.80 metres and a width limit of 1.06 metres, which would possibly require the assembly of the environmental chamber inside the aircraft. With a relatively low stress on the aircraft, the relatively benign nature of the complete maneuver, and the closed nature of the proposed experiment, it can be surmised that an even larger cargo aircraft can be used to perform the experiment with no additional concern for safety. This opens up the possibility of using considerably larger cargo aircraft, eg one among several available Boeing 747 freighters, whose cargo doors are multiple and very large, as seen on Fig. 8. That possibility opens the perspective for using much larger environmental chambers.

Aerodynamic constraints

There are possible challenges of operating a flying machine in a confined space such as an environmental chamber: managing the gas flows and limiting boundary effects come first. For example, it is well-known that wind-tunnel boundary effects can be deleterious to experimental results. Some of these effects can be mitigated by adding well-located louvers and to recirculate the air appropriately. The larger the environmental chamber, the more accurate the flight test relative to actual Titan conditions. Preliminary computational fluid dynamics can help lift these uncertainties, which should be relatively negligible for the foot-size aerial vehicles envisaged by the Titan exploration program.

Navigation issues

A proper, full-scale flight test environment should also be capable of replicating the conditions necessary for the unmanned vehicle to navigate its environment. The navigation system of any Titan-borne system is likely to includes a combined INS-vision navigation system. Algorithms used to extract system position and orientation rely on the necessary relations that link GPS readings and optical information in fixed environments. There is a risk, however, that such algorithms might be fooled if the airplane goes through perturbations, such as turbulence. In that case, the relation between optical and inertial readings could be temporarily de-correlated. The question as to whether such perturbations are observable and rejected requires more work than that envisioned to prepare the present paper.

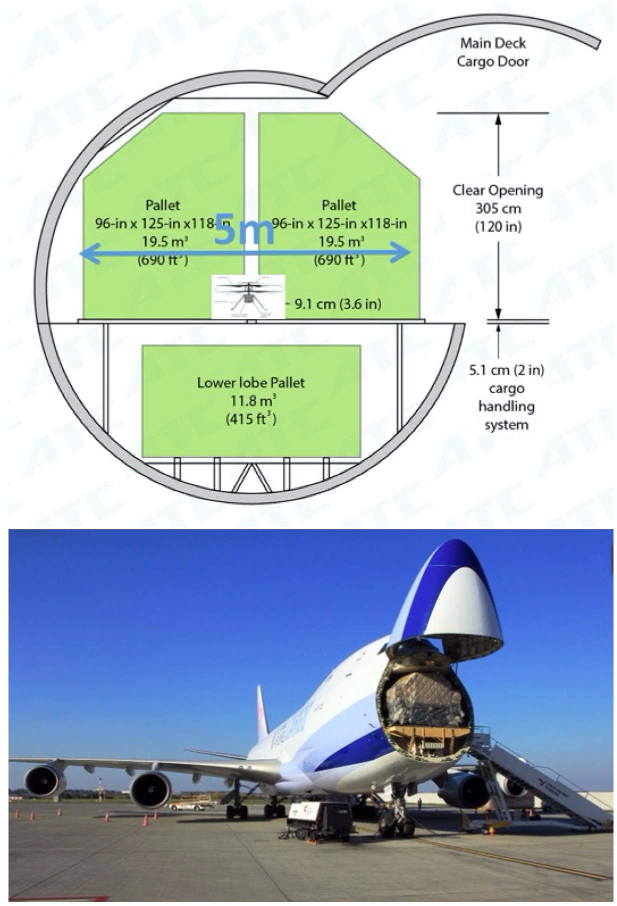

Figure 8. Top: B747 cargo aircraft. Relative dimensions are approximate. Bottom: 747 front cargo door.

Complementarity with other tests

The core benefit of the proposed test over ground-based tests is the possibility of exactly reproducing the gravity conditions encountered on Titan using an atmospheric device. In addition, it is also possible to effect large attitude changes on the airborne vehicles, something strictly impossible to do if the machine is suspended to a cable to emulate low gravitational conditions. Moreover, it becomes possible to obtain a better idea of the aerial vehicle behavior as it takes-off *from the ground*, including if it takes off not exactly horizontal, a distinct possibility when landing in a largely unknown area, and despite local leveling opportunities offered by robotic ground platforms. Last, it becomes possible to study the possibility of ”brownout” that may occur when dust gets blown away by the airflow created by the flying machine.

Other proposed uses

A high-fidelity Titan environment may be used in several ways. For example, there might be value testing Titan probe landing mechanisms, and rovers, at least those whose dimensions are acceptable. In addition, it might be possible to consider flight testing objects floating on or diving in Titan's methane lakes using the same overall approach by taking fluid tanks and flying them through Titan-g conditions.

Acknowledgements

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